

To appear in the *Astrophysical Journal Letters*.

The Inner Light Year of the Nearest Seyfert 1 Nucleus in NGC 4395

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ABSTRACT

The NRAO VLBA was used at 1.4 GHz to image the inner 550 mas (23 lt-years) of the nearest known Seyfert 1 nucleus, in the Sm galaxy NGC 4395. One continuum source was detected, with flux density $530 \pm 130 \mu\text{Jy}$, diameter $d < 11$ mas (0.46 lt-year), and brightness temperature $T_b > 2.0 \times 10^6$ K. The spectral power P of the VLBA source is intermediate between those of Sagittarius A and Sagittarius A* in the Galactic Center. For the VLBA source in NGC 4395, the constraints on T_b , d , and P are consistent with an origin from a black hole but exclude an origin from a compact starburst or a supernova remnant like Cassiopeia A. Moreover, the spectral powers of NGC 4395 at 1.4 and 4.9 GHz appear to be too low and too constant to allow analogy with SN1988Z, a suggested prototype for models of compact supernova remnants. The variable and warm X-ray absorber in NGC 4395 has a free-free optical depth much larger than unity at 1.4 GHz and, therefore, cannot fully cover the VLBA source.

Subject headings: galaxies: active - galaxies: individual (NGC 4395, UGC 07524) - galaxies: nuclei - galaxies: Seyfert - radio continuum: galaxies - X-rays: galaxies

1. MOTIVATION

The Seyfert 1 nucleus of NGC 4395 holds three unique distinctions. First, in the optical regime it is the least luminous Seyfert nucleus known, with an absolute blue magnitude of only

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$M_B = -9.8$ mag. On energetics grounds it is therefore essential to explore both black hole and stellar origins for the Seyfert activity (Filippenko & Sargent 1989; Filippenko, Ho, & Sargent 1993; Lira et al. 1999). Second, it is the only Seyfert nucleus known to be hosted by an Sm galaxy. Proving that the Seyfert traits of NGC 4395 are inconsistent with a stellar origin, but consistent with a black hole origin, would thus bolster claims of black hole ubiquity in the local universe (Magorrian et al. 1998). Finally, NGC 4395 lies at a distance $D = 2.6$ Mpc (Rowan-Robinson 1985), making it the nearest known Seyfert 1 nucleus. The corresponding scale is $10 \text{ mas} = 0.42 \text{ lt-year}$, so the inner light year can, in theory, be probed directly with the NRAO Very Long Baseline Array (VLBA). Direct imaging of radio emission on light-year scales can be a powerful discriminant between black hole and stellar origins: a black hole could launch jets (Falcke & Markoff 2000), while stellar processes could result in a compact starburst (Condon et al. 1991), a supernova remnant resembling Galactic ones (Green 1984), or a compact supernova remnant (Terlevich et al. 1995).

Recent observations of NGC 4395 with the NRAO Very Large Array (VLA) showed an unresolved source at a frequency $\nu = 1.4$ GHz, with a flux density $S = 1680 \pm 94 \mu\text{Jy}$; a diameter $d < 550 \text{ mas}$ (23 lt-years); and a spectral index $\alpha = -0.60 \pm 0.08$ ($S \propto \nu^\alpha$) between 1.4 and 4.9 GHz, indicating synchrotron emission from a nonthermal plasma (Ho & Ulvestad 2001). A VLA source of this strength is too weak to be imaged with the VLBA if just traditional self-calibration techniques are applied. However, the prospects for successfully imaging NGC 4395 with the VLBA are good if phase-referencing techniques are employed (Wrobel et al. 2000). Section 2 of this Letter reports the detection of one VLBA source at 1.4 GHz, using phase-referenced observations of a 550-mas region in NGC 4395. Section 3 examines the implications of this VLBA detection, plus published radio photometry, for black hole and stellar models for the origin of the radio emission. These data are shown to be consistent with an origin from a black hole but inconsistent with an origin from a compact starburst, a supernova remnant like Cassiopeia A, or a compact supernova remnant resembling SN 1988Z.

2. OBSERVATIONS, CALIBRATION, AND IMAGING

The VLBA (Napier et al. 1994) was used to observe NGC 4395 and calibrators on 2000 April 11 UT. Data were acquired in dual circular polarizations with 4-level sampling and at a center frequency 1.43840 GHz with bandwidth 32 MHz. Phase-referenced observations were made in the nodding style. A 3-minute observation of NGC 4395 was preceded and followed by a 2-minute observation of the phase, rate, and delay calibrator J1220+3431 (Wilkinson et al. 1998) about 1.5° from NGC 4395. Sources J1215+3448 and J1310+3220 were also observed, respectively, to check the astrometric accuracy and to align the phases of the independent baseband channels (Ma et al. 1998). Observation and correlation assumed a coordinate equinox of 2000. The *a priori* position adopted for NGC 4395 was very close to that in Ho & Ulvestad (2001).

Data editing and calibration were done using the 1999 December 31 release of the NRAO AIPS software and following the strategies outlined by Ulvestad (2000). After data deletion based on *a*

priori flags, data were deleted on all baselines involving any antenna observing below an elevation of 20° . Such elevation-based editing minimized differential ionospheric conditions between the lines of sight to J1220+3431 and NGC 4395. Despite this step, it was impossible to calibrate the phases on baselines to the VLBA antenna on Manua Kea in Hawaii, and those baselines were also deleted. This resulted in an observed baseline range of 240–5800 km and, for NGC 4395, a total of 129 baseline-hours of integration. VLBA system temperatures and gains were used to set the amplitude scale to an accuracy of about 5%, after first correcting for sampler errors. No self-calibrations were performed on NGC 4395.

The AIPS task IMAGR was used to form and deconvolve an image of the Stokes I emission from NGC 4395, with the visibility data being naturally weighted to optimize image sensitivity. This image, given in Figure 1, was restored with an elliptical-Gaussian beam with FWHM dimensions of 13.9 mas (0.59 lt-year) by 10.7 mas (0.45 lt-year) and elongation orientation of -20.3° , and has an rms noise value of 51 microjanskys (μJy) per beam area. The left panel of Figure 1 shows that only one VLBA source was detected above 4.5 times the rms noise, within a region centered on the unresolved VLA detection and spanning 550 mas (23 lt-years), which matches the upper limit to the diameter of the VLA detection at 1.4 GHz (Ho & Ulvestad 2001). A quadratic fit to the peak of the VLBA detection yielded a position of $\alpha(J2000) = 12^h25^m48^s.874$ and $\delta(J2000) = 33^\circ32'48''.69$. This position carries an absolute 2-dimensional error of 55 mas, set by the position error of J1220+3431 and verified with a phase-referenced image of J1215+3448. Given the signal-to-noise ratio of the VLBA detection of NGC 4395, its position can, in principal, be determined with an error of 1-2 mas (Ball 1975) and efforts are underway to reach that limiting accuracy.

The right panel of Figure 1 displays the inner 76 mas (3.2 lt-years) centered on the position of the VLBA detection. The VLBA source seems to be slightly resolved but this apparent resolution is likely to be artificial, due to the weakness of the source and/or residual errors in the phase calibration. As a gauge of the importance of the latter effect, before self-calibration an image of the strong source J1215+3448 had a peak intensity only 88% of the peak after phase self-calibration. For the VLBA detection of NGC 4395, (1) image integration over $N = 5.8$ beam areas gives a total flux density of $530 \pm 130 \mu\text{Jy}$, where the error is the quadratic sum of a 5% scale error and \sqrt{N} times the rms noise; and (2) a conservative estimate to the diameter is $d < 11$ mas (0.46 lt-year). Traits (1) and (2) imply that the VLBA detection has a brightness temperature $T_b > 2.0 \times 10^6$ K.

3. IMPLICATIONS

Figure 2 shows that the VLA detections of NGC 4395 (Ho & Ulvestad 2001) match the spectral powers and spectral index of Sagittarius A in the Galactic Center (Pedlar et al. 1989). The VLA size limit for NGC 4395, conveyed by the dimension of the left panel of Figure 1, is also comparable to the diameter of 26 lt-years for Sagittarius A (Pedlar et al. 1989). But the VLBA detection of NGC 4395 at 1.4 GHz is less powerful (Figure 2) and more compact (Figure 1, left panel) than

Sagittarius A. This hints that the VLBA source in NGC 4395 could be an extragalactic analog to Sagittarius A* (Falcke et al. 1998), thought to mark the massive black hole at the dynamical center of the Galaxy (Reid et al. 1999). An accurate position is not available for the dynamical center of NGC 4395 (Swaters et al. 1999). The position of the VLBA detection does agree with positions for the optical continuum (Cotton, Condon, & Arbizzani 1999), X-ray continuum (Ho et al. 2001), and nuclear H α emission (van Zee et al. 1998), but these agreements carry combined errors of order 1000 mas (42 lt-years). However, a stringent mass limit is available for a putative black hole in NGC 4395: Filippenko & Ho (2001) report detection of the Ca II infrared triplet lines in absorption from echelle spectra taken with the Keck I telescope, yielding estimates for the strength of the stellar contribution to the nuclear light ($M_B = -7.3$ mag) and the central LOS velocity dispersion ($\sigma \sim 30$ km s $^{-1}$), which, in combination with the star cluster size from *HST* images, limit any black hole mass to $M_{\text{BH}} \lesssim 80,000 M_{\odot}$.

An accreting black hole could launch jets. While Falcke & Markoff (2000) use a spectral analysis to build a case for a jet origin for Sagittarius A*, morphological evidence for an outflow would be far more compelling. In the case of NGC 4395, the VLBA source is unresolved at a linear resolution of 0.46 lt-year or 170 lt-days, and only 0.32 ± 0.26 times as strong as the VLA source spanning 23 lt-years or less. A few nearby galaxies have had their radio nuclei probed on similar scales, or even finer scales down to a resolution of 10 lt-days (eg, NGC 3031, Bietenholz, Bartel, & Rupen 2000). While jets or jet-like structures are invariably observed, those galaxies exhibit spectral powers at 1.5 GHz that are an order of magnitude, or more, above the power of the source in NGC 4395 at comparable VLA resolutions (Wrobel, Machalski, & Condon 2001). Still, the VLA and VLBA sources in NGC 4258 at 1.5 GHz (Cecil et al. 2000) are only about a factor of ten more powerful than their counterparts in NGC 4395. At a linear resolution of 0.94 lt-year, the VLBA source in NGC 4258 is resolved into two jets elongated over 5.9 lt-years. Similar jets, if present in NGC 4395, could account for some of the VLA flux density missing from Figure 1: a deeper VLBA image of NGC 4395 is required to search for such jets. The present VLBA detection could then correspond to the brightest region in the jets, an hypothesis that could be tested with VLBA imaging at higher linear resolution.

On energetics grounds it is reasonable also to explore a stellar origin for the Seyfert activity in NGC 4395 (Filippenko, Ho, & Sargent 1993; Lira et al. 1999). In the radio regime, stellar processes could result in a compact starburst, a supernova remnant resembling Galactic ones, or a compact supernova remnant.

For a compact starburst, Condon et al. (1991) use an empirical scaling relation between thermal and nonthermal radio continuum, based on more extended star-forming galaxies with thermal electron temperature $T_e = 10^4$ K, to derive a limiting brightness temperature of $T_b \lesssim 10^5$ K at 1.4 GHz. The VLBA source in NGC 4395, with brightness temperature $T_b > 2.0 \times 10^6$ K, clearly exceeds this limit, excluding a compact starburst origin.

The Galactic supernova remnant Cassiopeia A, of age $t \lesssim 400$ years, has spectral powers and

a spectral index (Baars et al. 1977; Green 1984; Filippenko, Ho, & Sargent 1993) very similar to those derived from the VLA detections of NGC 4395 (Ho & Ulvestad 2001). These photometric similarities are displayed in Figure 2. The upper limit $d = 23$ lt-years to the diameter of the VLA source in NGC 4395 is also consistent with the diameter $d = 13$ lt-years for Cassiopeia A (Green 1984). But the VLBA source in NGC 4395 is about a third as powerful (Figure 2) and considerably more compact ($d < 0.46$ lt-year) than Cassiopeia A. This VLBA size constraint strongly excludes further analogy with Cassiopeia A.

Could the VLBA source in NGC 4395 be a compact supernova remnant (cSNR) whose evolution is governed by a supernova expanding into dense circumstellar material (Terlevich et al. 1995)? Such an interpretation encounters some successes and some difficulties (Filippenko, Ho, & Sargent 1993; Lira et al. 1999). In the optical regime, published images of NGC 4395 plus the POSS revealed the presence of a starlike nucleus, visible at similar brightness levels since 1956 May 8 UT and implying an age $t \gtrsim 36$ years in 1992. Lira et al. (1999) find that, while this slow blue photometric evolution could just be a signpost of a cSNR of age $t \sim 300$ years, the observed line properties roughly match those expected for a cSNR of age $t \sim 34$ years. The large-amplitude variability observed on time scales of days to months, in both the optical and X-ray regimes, remains a problem for the cSNR model.

In the radio regime, the record of photometric evolution of the VLA source, while sparse, supports approximate constancy over 1–2 decades at 1.4 and 4.9 GHz, since 1982 (Moran et al. 1999; Ho & Ulvestad 2001). Also, Heeschen & Wade (1964) used the NRAO 91-m telescope in 1963 to set an upper limit of 0.2 Jy for the peak flux density of NGC 4395 at 1.4 GHz. Is this record consistent with a cSNR origin? Models for cSNRs do not, as yet, predict radio light curves, although Terlevich et al. (1995) do remark on the relevance of SN 1988Z, a radio supernova, to their models. Figure 3 shows the model light curves for SN 1988Z at 1.4 and 4.9 GHz, based on three years of monitoring in the radio regime (Van Dyk et al. 1993) but extrapolated to an age of 50 years. The powers of the VLA detections of NGC 4395, measured on 1982 Feb 8 UT and 1990 Mar 3 UT by Moran et al. (1999) with matched resolutions, and on 1999 Aug 29 and Oct 31 UT by Ho & Ulvestad (2001) also with matched resolutions, are plotted at their minimum possible ages assuming a reference date of 1956 May 8 UT. (No point appears for the VLBA detection due to concern about the effects of source resolution between VLA and VLBA scales.) The power of the 91-m upper limit, obtained during 1963 between Feb 1 UT and Dec 31 UT, is also plotted at the minimum possible age of about 7.2 years relative to the same reference date. Figure 3 shows that NGC 4395 is observed to be less powerful than SN 1988Z, by factors ranging from at least 60 at an age of about 7 years to about 100–700 at an age of 43 years. This latter discrepancy could reflect the failure of the SN 1988Z model after a few decades but model problems are unlikely through the first decade (Hyman et al. 1995). The spectral powers of NGC 4395 at 1.4 and 4.9 GHz thus appear to be too low since 1963 and too steady since 1982 to allow analogy with SN 1988Z. The former trait is more constraining than the latter, as the degree of variability could be artificially suppressed if only a small fraction of the VLA emission arises from a cSNR.

In summary, for the VLBA source in NGC 4395, the constraints on T_b , d , and P are consistent with an origin from a black hole but exclude an origin from a compact starburst or a supernova remnant like Cassiopeia A. Also, the spectral powers of NGC 4395 at 1.4 and 4.9 GHz seem both too low and too stable for analogy with SN 1988Z, a suggested prototype for models of compact supernova remnants. Future studies of the VLBA source in NGC 4395 should focus on measuring its spectral index, reducing the upper limit to its diameter or seeking evidence for jet-like structures, assessing its astrometric stability (cf. Wrobel 2000), and imaging the missing VLA flux density.

Like other Seyfert galaxies, NGC 4395 exhibits copious evidence for thermal nuclear plasma. Estimates of the associated free-free optical depths τ_{ff} at 1.4 GHz can constrain the relative geometries of the thermal and nonthermal plasmas. Equation 1 of Ulvestad et al. (1999) reduces to $\tau_{\text{ff}} = 0.038 T_e^{-1.35} E$ at 1.4 GHz for a thermal plasma with electron temperature T_e in units of K and emission measure E in units of $\text{cm}^{-6} \text{ pc}$. While T_e is either readily observed or plausibly estimated, neither condition generally applies to E . However, a notable exception is the thermal plasma responsible for the variable warm X-ray absorber in NGC 4395 (Iwasawa et al. 2000). For this plasma, $T_e = 10^6$ K is plausibly adopted, the column density is measured, and the variability time scale sets a lower limit to the density. The latter two quantities imply $E \gtrsim 2 \times 10^{13} \text{ cm}^{-6} \text{ pc}$, which, in combination with $T_e = 10^6$ K, leads to $\tau_{\text{ff}} \gtrsim 6000$. The variable warm X-ray absorber in NGC 4395 has a free-free optical depth much larger than unity at 1.4 GHz and, therefore, cannot fully cover the VLBA source. Arguments such as these should be folded into discussions of unifying structures for the inner regions of quasars (eg, Elvis 2000).

The authors thank Dr. J. Ulvestad for discussions. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration. NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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Fig. 1.— VLBA images of Stokes I emission from NGC 4395 at a frequency of 1.4 GHz. Hatched ellipse shows the restoring beam area at FWHM. Contour levels are ± 2 , ± 4 , and ± 6 times the image rms noise level of $51 \mu\text{Jy}$ per beam area. Negative contours are dashed and positive ones are solid. *Left*: Inner 550 mas (23 lt-years) centered on the position of the VLA detection at 1.4 GHz by Ho & Ulvestad (2001). The image size matches the upper limit to the diameter of the unresolved VLA detection. One-sigma position errors are shown by the cross for the VLA detection and by the cross with a gap for the VLBA detection. *Right*: Inner 76 mas (3.2 lt-years) centered on the position of the VLBA detection.

Fig. 2.— Spectral power as a function of frequency. One-sigma error bars are shown for NGC 4395. Error bars for the Galactic sources are smaller and not shown to reduce plot clutter.

Fig. 3.— Spectral powers at 1.4 GHz (circles) and 4.9 GHz (squares) as a function of age. The model light curves for SN 1988Z, shown at monthly intervals, are from three years of monitoring in the radio regime but extrapolated to an age of 50 years. The data points are from measurements of NGC 4395 during 1963–1999 but referenced to 1956 May 8 UT, the epoch of the first optical detection of the Seyfert 1 nucleus. One-sigma error bars are shown for NGC 4395.

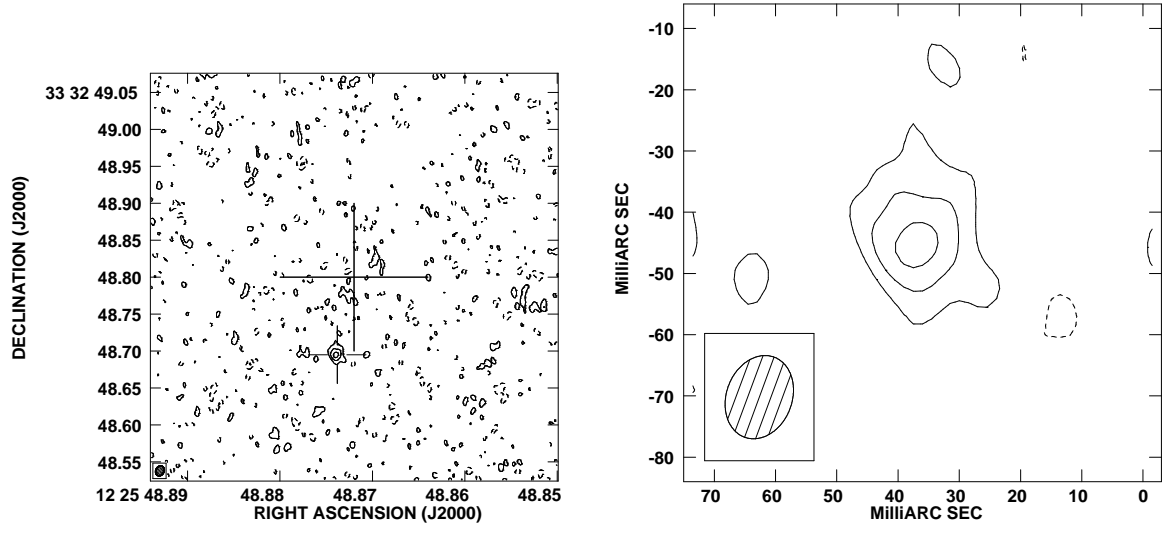


Figure 1

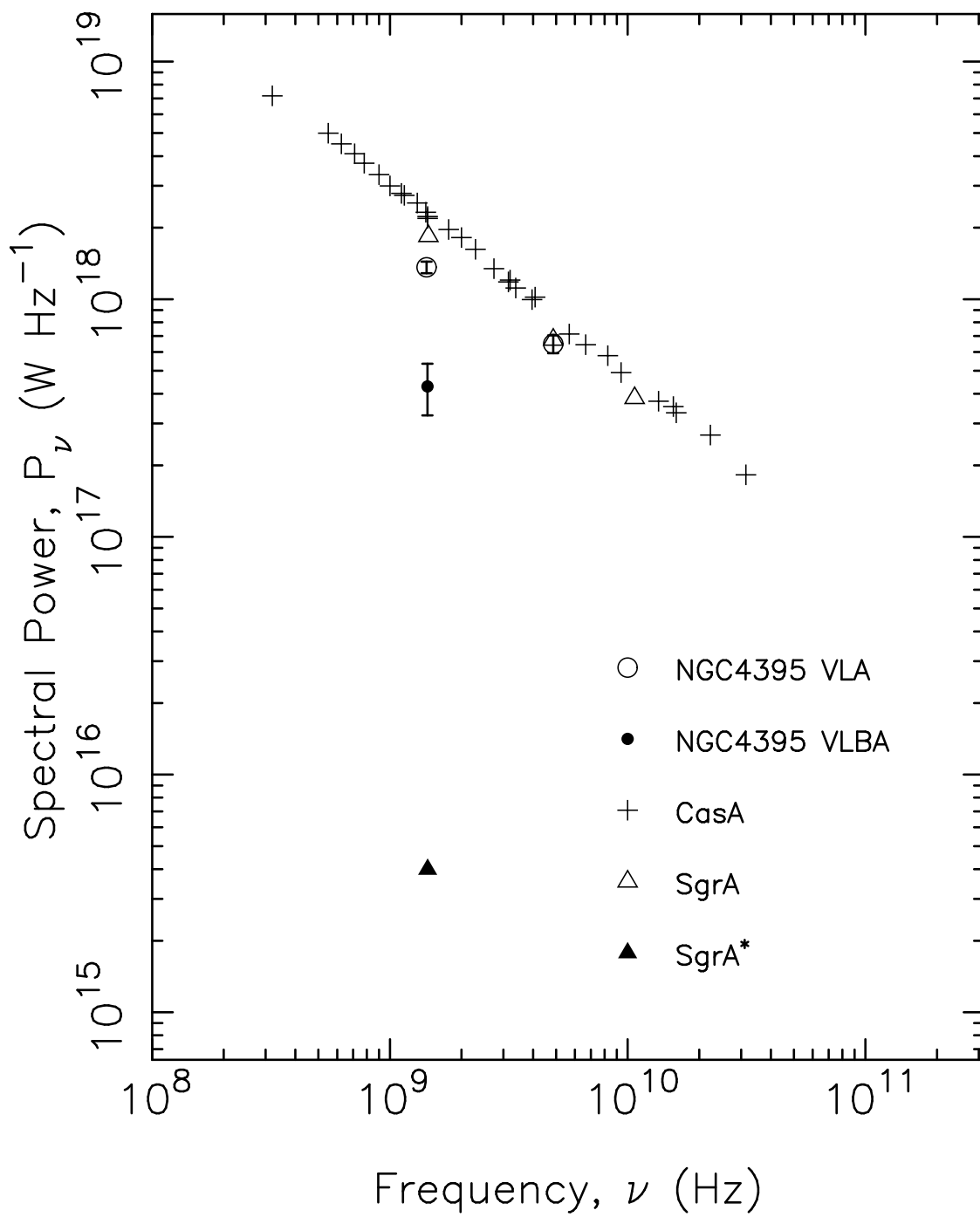


Figure 2

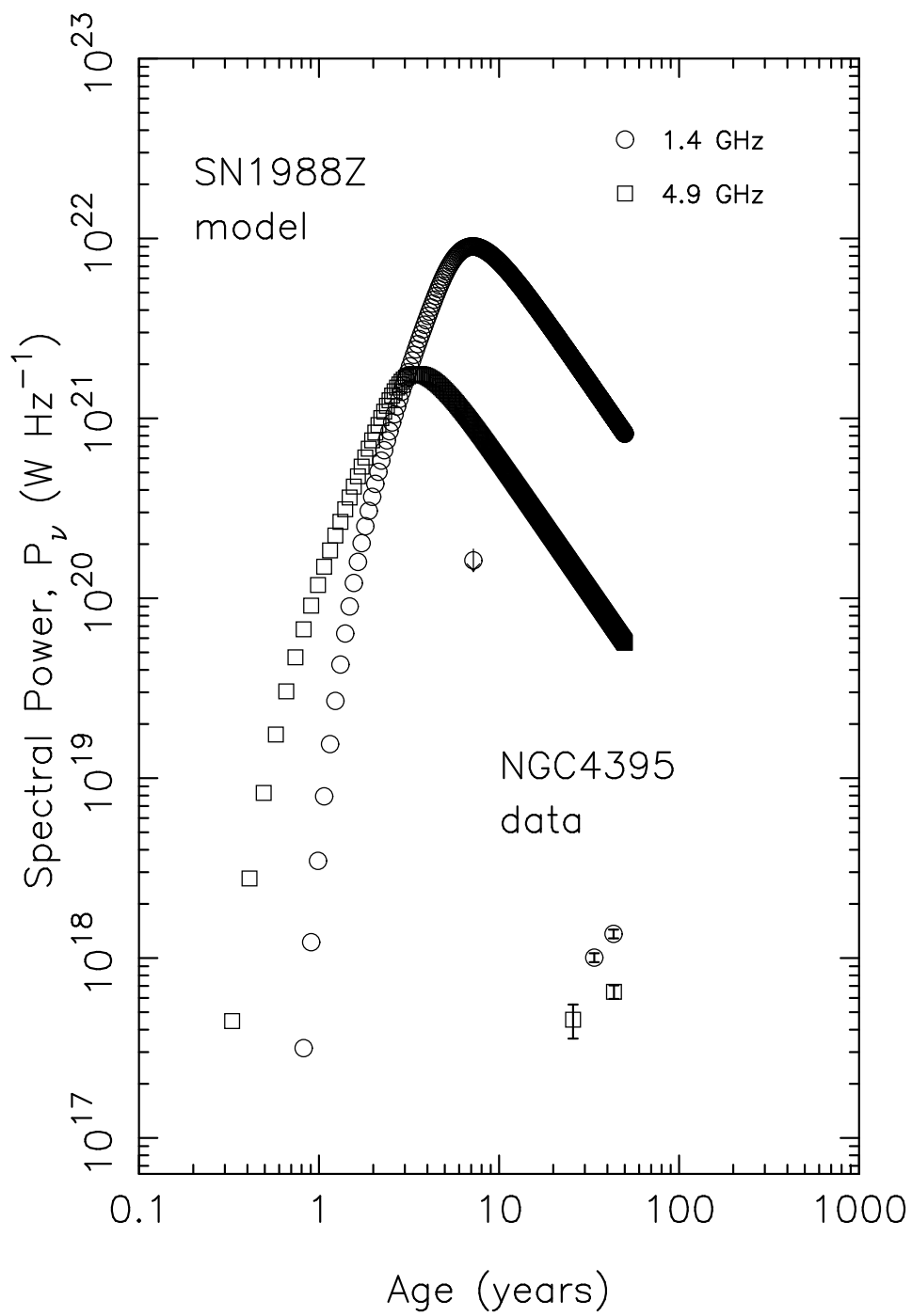


Figure 3